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Ioffe Institute
6th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 22–26, 1998.

Optical effect of electric field on indirect exciton luminescence in double quantum wells of GaAs

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Studies of double quantum wells (DQW) have attracted considerable interest from both theoretical and experimental point of view. This interest is caused partially by the possibility to utilize the electronic properties of DQWs in various optoelectronic devices. From the other hand the physical interest arises from the considering the DQW system as a promising candidate to study excitonic properties with respect to the single-exciton problem as well as to the exciton-exciton interaction processes. The central point of physical interest in DQW is the study of indirect exciton (IX) transition (consisting of an electron (e) and a hole (h) localized in different quantum wells (QW) of the same DQW) which possesses a much longer radiative lifetime relative to the direct exciton (e and h are located within the same QW). This fact allows one to create the IX gas of high density even at moderate pumping intensities and as a consequence to expect the revealing on experiment of some interesting properties related to collective excitation in the IX gas of high density, which were predicted theoretically (see [1] and references therein).

As concerns of experimental investigations, there are very few papers [2, 3] which report the revealing of collective phenomenon in the IX system, namely the reduction of the IX line width in GaAs DQW [2] and the observation of the huge broad band noise in the Hz range scale of the IX line integrated intensity in coupled QW of AlAs/GaAs induced by a magnetic field [3].

In the present report we study the IX line shape in photoluminescence (PL) spectra originating from the DQW of GaAs depending on the electric field value applied to the structure. We observe unusual IX line shape behaviour in the definite range of bath temperatures and pumping intensities and discuss our results in terms of possible revealing of the collective excitations in a dense IX gas which were predicted in [1].

Samples and experimental details

The samples were taken from wafer NU1117 consisting of 1 mm GaAs buffer layer followed by three DQWs. The structure was grown in Nottingham University (UK) by MBE at $T = 630$ °C on 0.4 mm thick (001) GaAs substrate. The thickness of the narrow barriers of $Al_{0.33}Ga_{0.67}As$ between the QWs in DQW is 3.82 nm and that of the QWs in DQW differ by 2ML (0.57 nm) of GaAs with layer widths (QW/barrier/QW in nm) of 20.07/3.82/19.50, **10.18/3.82/9.61** and 8.20/3.82/7.63. In the present contribution we will concentrate on the results obtained on the DQW shown in bold. A constant electric field V_{dc} was applied across the whole structure (Fig. 1a) between two indium contacts deposited on the substrate surface and the sample's face with DQWs. The latter contact was made with single pin hole giving the possibility to collect luminescence

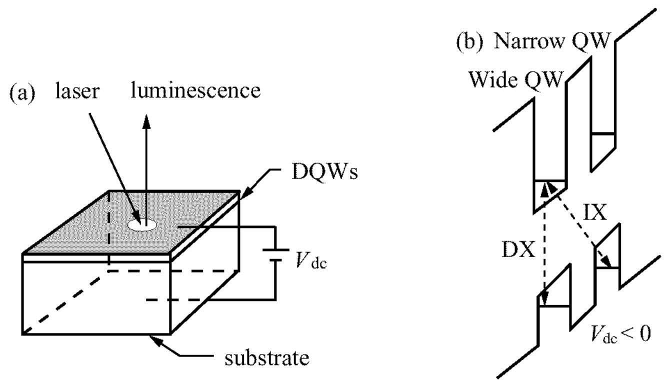

Fig 1. Experimental setup (a) and schematic band diagram of "indirect regime" (b).

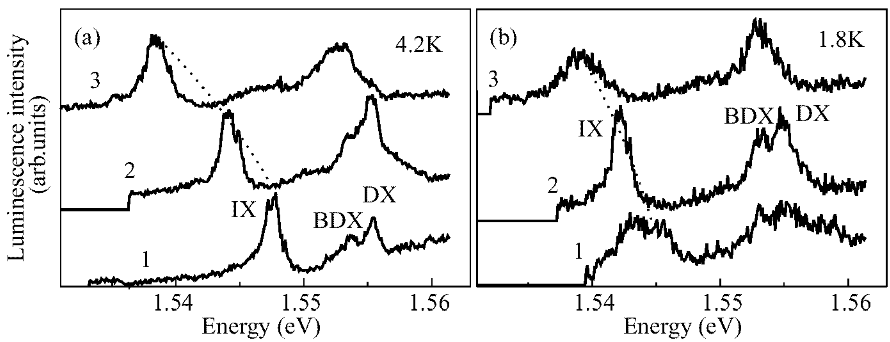

Fig 2. PL spectra taken at $P = 1$ mW and $\lambda = 765.2$ nm (a): $T = 4.2$ K, $V_{dc} = -0.5$ V (1), -1 V (2), -1.5 V(3) and (b): $T = 1.8$ K, $V_{dc} = -0.8$ V (1), -1.3 V(2), -1.6 V (3).

which was excited by the cw-Ti-sapphire laser ($730 < \lambda < 815$ nm, max power P up to 100 mW) providing the below barrier excitation and laser beam was focused down to a spot of 0.1–0.2 mm in diameter. Bath temperature T_b was varied in the range of $1.8 < T_b < 10$ K.

Experimental results and discussion

Experiments were carried out in the "indirect regime" schematically shown in Fig. 1b which is characterized by the lowest energy position of the IX relative to the DX in PL. In the regime of moderate electric fields ($< 10^5$ V/cm) across the DQW when quadratic Stark shift is negligible, DX line position should be electric field independent while that of IX should vary essentially with V_{dc}. This is clearly demonstrated by the data of Fig. 2 which shows V_{dc} influence on the PL spectra taken at $T_b = 4.2$ K (Fig. 2a) and $T_b = 1.8$ K (Fig. 2b). Indeed, with increasing V_{dc} value DX line and line of DX bound to the impurity (labelled as BDX) have the same spectral positions while IX line considerably shifts to lower energies, reflecting the exact value of electric field V_{DQW} applied across the particular DQW under investigation.

It is seen that at $T_b = 4.2$ K (Fig. 2a) IX line shifting to lower energies with increasing V_{dc} (and hence V_{DQW}) has approximately unchanged spectral shape — its full width at half maximum (FWHM) slightly increases while at $T_b = 1.8$ K (Fig. 2b) IX behaves in a different way. Really IX line is wider at low and high V_{dc} (curves 1

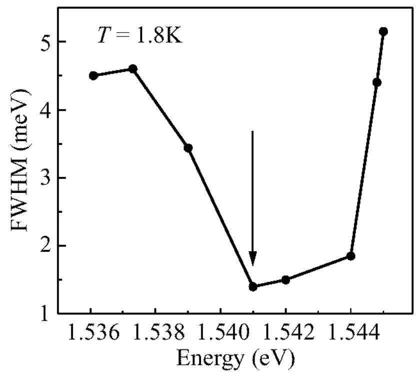

Fig 3. The IX FWHM value versus its spectral position (reflecting the particular value of V_{DQW} taken at $P = 1$ mW and $T = 1.8$ K.

and 3 in Fig. 2b) and becomes considerably narrower at voltages in between (curve 2 in Fig. 2b). This FWHM evolution at $T_b = 1.8$ K is clearly seen from the plot shown in Fig. 3.

To understand this phenomenon let us consider how the changes in the external electric field (and hence in V_{DQW}) can affect the FWHM of IX PL line. First of all the width of IX line in DQW is inhomogeneous and is determined by a wide range of transition energies of IX localized on interface potential fluctuations which are caused mainly by the well (barrier) width fluctuations in the samples of very high quality. In the samples grown with growth interruption the lateral (in plane) size of QW (barrier) width fluctuations $L_{x,y}$ is much larger than exciton diameter a_{ex}, so PL spectrum consists of several distinctly separated lines, originating from the recombination of excitons localized in corresponding parts of QW [4]. In the same time in samples grown without interruption of growth (as corresponds to our case) the $L_{x,y}$ and a_{ex} are of the same order [4] and hence typical PL spectrum consists of a single broad line.

The dramatic narrowing of the IX line observed at $T_b = 1.8$ K (Fig. 3) with increasing V_{DQW} (when spectral position of IX line shifts to lower energies) we attribute to a phase transition in the exciton system from a normal regime to a collective regime or condensed state which appears in the dense gas of IX. Indeed if the exciton system makes a transition to a new collective (condensed) state, which is characterized by a long-range order, the excitonic energy levels will be determined by a potential averaged over the size much larger than the diameter of a single exciton a_{ex}, and hence PL line broadening due to the interface roughness will be washed out which eventually lead to the drastic line sharpening.

Our results demonstrate not only IX line narrowing (as it was reported in [2]) but also its broadening with further increase of V_{dc} (Fig. 3). Electric field applied to the DQW changes the overlap of the wavefunctions of e and h of IX in the growth direction and hence the radiative lifetime of IX τ_R which is inversely proportional to that overlap. This makes it possible to increase τ_R essentially (by increasing V_{dc}) and as a result to make exciton gas thermalized to bath temperature better. So the effective tuning of τ_R allows one to escape the problem of short exciton radiative lifetimes which usually is the main reason preventing exciton condensation to a new phase. Thus we conclude that the IX line narrowing is due to electric field induced increasing of τ_R. Evidently the formation of a new condensed state (revealing in our case as a line narrowing) should be more favourable at lower temperatures which is in full agreement with our data (compare Fig. 2a and 2b). The reason why PL line broadens with further increase of V_{dc} is more complicated and can be understood on the base of theoretical calculations which were performed in [1]. Authors of paper [1] considered the system of IX in DQW and predicted the possibility of a new condensed phase appearance in definite range of parameters, namely the IX concentration (or the in-plane separation of two neighbouring excitons) and the distance D between e and h of IX in the growth direction (another words IX dipole moment eD value). This theoretical analysis shows that the main part of the energy of interacting IX system is given by dipole-dipole repulsion interaction though there is the definite range of parameters where the energy of IX system is decreased (comparing to the non-interacting excitons) and hence a new condensed phase is the lowest stable energy state of the IX system. We believe that this is the case when line narrowing takes place (Fig. 3). Further increase of V_{dc} inevitably leads to increasing of interparticle distance D of IX (and hence its averaged dipole moment) which leads to predominance of dipole-dipole repulsion interactions and this as a consequence breaks down the exciton condensed state. As a result IX line broadens and its FWHM acquires the same value (at high V_{dc} — or low energy spectral position) as it was before condensation (at low V_{dc} — or high energy spectral position) — see Fig. 3.

It is important to note that huge oscillations in IX PL intensity were detected at V_{dc}'s values which correspond to the sharp increase of FWHM (shown as vertical arrow in Fig. 3). These oscillations can be interpreted in terms of two phases (normal and condensed) coexistence in the IX system which should take place near the point of phase transition. It should be stressed out that the effect of IX line narrowing (at $T = 1.8$ K) is more pronounced at used pumping intensity P of 1 mW which corresponds to IX concentration of 10^{10} cm^{-2} while it is still detectable at $0.25 < P < 5$ mW. At lower (higher) pumping intensities (IX gas concentrations) the in-plane interparticle distances are too long (short) to form a condensed state (as expected from the calculations in [1]) in a full range of V_{dc} values investigated.

In conclusion we observed IX line narrowing (accompanied by huge oscillations of the IX line PL intensity) at $T = 1.8$ K in DQW of GaAs. This is believed to be the evidence of new condensed state formation in a dense gas of IX. Altering the electric field strength allowed us to perform fine tuning of the IX radiative lifetime and its averaged dipole moment — the two crucial parameters which govern the condensed state appearance (at fixed IX gas concentration and bath temperature), another words the external electric field can be used as an effective tool to map out the phase diagram of a dense IX gas.

We are gratefully thankful to Prof. A. A. Kaplyanskii for permanent attention and support of this work, to Prof. Yu. E. Lozovik for fruitful discussions, to Mr. D. A. Mazurenko for help in experiments and to Russian Foundation for Basic Research No. 98-02-18296 for financial support.

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